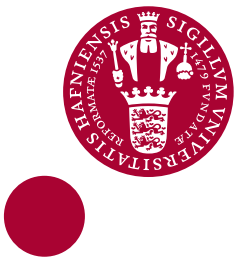

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Exchange of CO_2 in Arctic tundra: impacts of meteorological variations and biological disturbance

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Abstract. An improvement in our process-based understanding of carbon (C) exchange in the Arctic, and its climate sensitivity, is critically needed for understanding the response of tundra ecosystems to a changing climate. In this context, we analyzed the net ecosystem exchange (NEE) of CO_2 in West Greenland tundra (64° N) across eight snow-free periods in eight consecutive years, and characterized the key processes of net ecosystem exchange, and its two main modulating components: gross primary production (GPP) and ecosystem respiration (R_{eco}). Overall, the ecosystem acted as a consistent sink of CO_2, accumulating -30 g C m^{-2} on average (range -17 to -41 g C m^{-2}) during the years 2008-2015, except 2011 that was associated with a major pest outbreak. The results do not reveal a marked meteorological effect on the net CO_2 uptake despite the high inter-annual variability in the timing of snowmelt, start and duration of the growing season. The ranges in annual GPP (-182 to -316 g C m^{-2}) and R_{eco} (144 to 279 g C m^{-2}) were >5 fold larger and they were also more variable (Coefficients of variation are 3.6 and 4.1 % respectively) than for NEE (0.7 %). GPP and R_{eco} were sensitive to insolation and temperatures; and there was a tendency towards larger GPP and R_{eco} during warmer and wetter years. The relative lack of sensitivity of NEE to climate was a result of the correlated meteorological response of GPP and R_{eco}. During the 2011 anomalous year, the studied ecosystem released 41 g C m^{-2} as biological disturbance reduced GPP more strongly than R_{eco}. With continued warming temperatures and longer growing seasons, tundra systems will increase rates of C cycling although shifts in sink strength will likely be triggered by factors such as biological disturbances, events that will challenge the forecast of upcoming C states.

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1 Introduction

Quantifying the carbon (C) dynamics of the terrestrial biosphere is a major concern for earth system science (Williams et al., 2005). Arctic organic C storage has received increased attention in recent years due to large potential for carbon release following thaw (Koven et al., 2011) that could create a positive feedback on climate change and accelerate the rate of global warming. Recent reviews have estimated the Arctic terrestrial C pool to be 1400-1850 Pg C, accounting for more than twice of the atmospheric C pool (Hugelius et al., 2014; McGuire et al., 2009; Tarnocai et al., 2009) and approximately 50% of the global soil organic C pool (AMAP, 2011; McGuire et al., 2009). Further, Arctic ecosystems have experienced an intensified warming tendency, reaching almost twice the global average (ACIA, 2005; AMAP, 2011; Callaghan et al., 2012c; Serreze and Barry, 2011). The projected Arctic warming is also expected to be more pronounced in coming years (AMAP, 2011; Callaghan et al., 2012a; Christensen et al., 2007; Grøndahl et al., 2008; Meltofte et al., 2008) and temperatures, precipitation and growing season length will likely increase in the Arctic (ACIA, 2005; Christensen et al., 2007; Christensen et al., 2004; IPCC, 2007). Given this situation, an improvement in our process-based understanding of CO_2 exchanges in the Arctic, and their climate sensitivity, is critical (McGuire et al., 2009).

In recent decades, eddy covariance has become a fundamental method for carbon flux measurements on a landscape scale (Lund et al., 2012; Reichstein et al., 2005; Lasslop et al., 2012). Eddy covariance data, Net Ecosystem Exchange of CO_2 (NEE), can be gap-filled and subsequently separated into its modulating components Gross Primary Production (GPP) and Ecosystem Respiration (R_{eco}) using flux partition algorithms (Reichstein et al., 2005). Those techniques are critical to provide a better understanding of the C uptake versus C release behaviour (Lund et al., 2010); but they also allow for an examination of the environmental effects on ecological processes (Hanis et al., 2015). However, large gaps in the measured fluxes may introduce significant uncertainties in the C budgets estimations. Moreover, GPP and R_{eco} estimates can be calculated in different ways. Some algorithms fit a temperature-respiration curve to night-time data (Reichstein et al., 2005; Lasslop et al., 2012); others calculate R_{eco} from a light-response curve (Gilmanov et al., 2003; Lindroth et al., 2007; Lund et al., 2012; Mbufong et al., 2014; Runkle et al., 2013). Unfortunately, different interpretations of the flux gap-filling and partitioning lead to different estimates of NEE, GPP and R_{eco}, as well as undefined uncertainties.

Understanding the inter-annual C exchange variability in the Arctic tundra is challenging due to extreme conditions through much of the growing season, and the patchy nature of the landscape linked to micro-topography. Different eco-types present different C exchange rates (Bubier et al., 2003), and because the composition of vegetation varies as a response to environmental changes (Glenn et al., 2006), C exchange presents correlated responses. Synthesis studies have found a significant spatial variability in NEE (Lafleur et al., 2012; Mbufong et al., 2014) between different sites in the Arctic tundra (Lindroth et al., 2007; Lund et al., 2010) but also a large temporal variability within sites (Aurela et al., 2004; Aurela et al., 2007; Christensen et al., 2012; Grøndahl et al., 2008; Lafleur et al., 2012). Minor variations in GPP and R_{eco} may promote changes in the C balance state (Williams et al., 2000; Tagesson et al., 2012; Lund et al., 2010; Arndal et al., 2009; Elberling et al., 2008; IPCC, 2007). With continued warming temperatures and longer growing seasons, tundra systems will likely have enhanced GPP and R_{eco} rates, but long-term data to investigate these responses is rare. Further, the effects on net CO_2 sequestration are not known, and may be altered by long-term processes such as vegetation shifts and short-term disturbances like insect pest outbreaks, complicating the prognostic forecast of upcoming C states (Callaghan et al., 2012b; McGuire et al., 2012). Consequently, there is a need to understand how C cycle behaves over time scales from days to years, and the links to environmental drivers. There is a lack of reference sites from where full measurement-based data is available, documenting the basic carbon stocks and fluxes at the terrestrial catchment scales. Here we investigate the functional responses of C exchange to environmental characteristics across eight snow-free periods in eight consecutive years in West Greenland.

The main objectives of this paper are (1) to explore the uncertainties in NEE gap-filling and partitioning obtained from different approaches, (2) to determine how C uptake and C storage respond to the meteorological variability and assess the

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resiliency of the studied ecosystem to meteorological variability, and (3) to identify how the environmental forcing affects not only the inter annual-variability, but also the hourly, daily, weekly and monthly variability. The intention of this paper is to elaborate on the information gathered in an existing catchment area under an extensive cross-disciplinary ecological monitoring program in low Arctic West Greenland, established under the auspices of the Greenland Ecosystem Monitoring (GEM) (http://www.g-e-m.dk). Using a long-term (8 years) dataset to explore uncertainties in NEE gap-filling and partitioning methods and to characterise the inter-annual variability of C exchange in relation to driving factors can provide a novel input into our understanding of land-atmosphere CO_2 exchange in Arctic regions. The time series is focused on the snow-free period, our measurements typically start around the end of the snow melt (ca. May-June) and extend until the freeze-in period (between September-October). Once the snow melts, the growing season (i.e. the part of the year when the weather conditions allow plant growth) has been reported as the most relevant period defining both spatial (Lund et al., 2010; Mbufong et al., 2014) and temporal (Groendahl et al., 2007; Lund et al., 2012; Aurela et al., 2004) CO_2 variability.

2 Materials and methods

2.1 Site description

The field measurements were conducted in the low Arctic Kobbefjord drainage basin, South-western Greenland (64° 07' N; 51° 21' W) (Figure 1a). The study area is placed ca. 20 km SE of Nuuk, the Greenlandic capital. Kobbefjord has been subject to extensive environmental research activities (the Nuuk Ecological Research Operations) since 2007 (http://www.nuuk-basic.dk). The lowland site is located 500 meters from the South-eastern shore of the bottom of Kangerluarsunnguaq Fjord (Kobbefjord), and 500 meters from the Western shore of the 0.7 km^2 great lake called "Badesø" (Figure 1b). Three glaciated mountains, all above 1000 m. asl., surround the site. The landscape consists on a fen area surrounded by heath, copse and bedrock. The current fen vegetation is dominated by *Scirpus caespitosus*, whereas the surroundings are dominated by heath species such as *Empetrum nigrum*, *Vaccinium uliginosum*, *Salix glauca* and copse species such as *S. glauca* and *Eriophorum angustifolium* (Bay et al., 2008). Kobbefjord belongs to the "Arctic shrub Tundra" according to Skip Walker's BioClimate classification (CAVM Team, 2003) based on the summer warmth index (SWI). In 2010 and 2012 this area went out of the Arctic zone as most of the other SW-Greenlandic locations. For the 1961-1990 period, the mean annual air temperature was -1.4 °C and the annual precipitation was 750 mm (Cappelen, 2013). The sun light hours between May and September range from 14 to 21 hours. Outcalt's frost number (Nelson and Outcalt, 1987) indicates that discontinuous permafrost should be present, although no permafrost has been found. Nonetheless, thin lenses of ice may remain until late summer.

2.2 Measurements

We have used eddy covariance (EC) data measured during the snow-free period from 2008 to 2015. The EC measurements were conducted in the EddyFen station (Figure 1b and 1c), located in a wet lowland, 40 m. asl. The EC tower is equipped with a closed-path infrared CO_2 and H_2O gas analyzer LI-7000 (LI-COR Inc, USA) and a 3D sonic anemometer Gill R3-50 (Gill Instruments Ltd, UK). The anemometer was installed at a height of 2.2 m, while the air intake was attached 2.0 m above terrain on the steel stand. Adjacent to the EddyFen station, an independent system (Figure 1b and 1c) measures round-the-clock CO_2 fluxes from soils by an automatic chamber (AC) method based on Goulden and Crill (1997). The transparent chambers, each covering a known surface area of 60 cm by 60 cm, with a height of 30 cm, can be opened and closed sequentially for 5+5 min every hour. When the chamber closes, a CO_2 analyzer (SBA-4, PP Systems, UK) monitors both the CO_2 concentration by a close loop of tubing (further information about the set up can be found in Mastepanov et al. (2012). Nearly 20 m from the EddyFen station, the automated SoilFen (Figure 1b and 1c) station provides environmental variables such as air and surface temperature (Vaisala HMP45C), soil temperature at different depths (Campbell scientific 10ST) and relative humidity (Vaisala HMP45C). Two km from these stations, an automatic weather station provides complementary

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ancillary data as short & long wave radiation (with a CNR1 instrument), photosynthetic active radiation (with a Kipp & Zonen PAR Lite instrument), precipitation (using an Ott Pluvio instrument) and snow depth (with a Campbell Scientific SR 50). The water table depth data has been monitored using a piezometer located next to each of the six auto chambers. Finally, a robust daily estimate of the timing of snowmelt was analyzed at a pixel level from a time-lapse camera (HP e427) located at 500 m. asl. (Westergaard-Nielsen et al., 2013).

2.3 Data handling

2.3.1 Data collection and pre-processing

Data collection from the EddyFen station was performed using Edisol software (Moncrieff et al., 1997). Raw data files were processed using EdiRe software (Robert Clement, University of Edinburgh) calculating the CO_2 fluxes on a half hourly basis. The flux processing integrated despiking (Højstrup, 1993), 2D rotation, time lag removal by covariance optimization, block averaging, frequency response correction (Moore, 1986) and Webb-Pearman-Leuning correction (Webb et al., 1980). For more information, see Westergaard-Nielsen et al. (2013). Ancillary data (air temperature, soil temperature, incoming short wave radiation, relative humidity, PAR and precipitation) have been temporally resampled using R (https://www.r-project.org/). Time-series-related packages such as *zoo* (Zeileis and Grothendieck, 2005), *xts* (Ryan and Ulrich, 2014) and *lubridate* (Grolemund and Wickham, 2011) were used to get the ancillary data aligned with the flux data in half-hourly basis.

2.3.2 Generating robust and complete flux time series

Before the CO_2 flux time series were analysed, three different processing techniques (u*filtering, gap-filling and partitioning) were applied to (1) filter the NEE data for quality, (2) fill the NEE gaps and (3) separate NEE into GPP and R_{eco}. The identification of periods with insufficient turbulence conditions (indicated by low friction velocity u*) is important to avoid biases and uncertainties in EC fluxes. To control the data quality, here the u* thresholds were bootstrapped by identifying conditions with inadequate wind turbulence according to the method described in (Papale et al., 2006) and the implementation in Papale et al., (In prep.). The data were sub-setted to similar environmental conditions, aside from friction velocity: 8 years and 7 temperature classes. Within each year/temperature subclass the u* threshold (5%, 50% and 95% of bootstrap) was estimated in 1000 samples per year. The subsequent gap-filling and partitioning were then applied using those different thresholds to propagate the uncertainty of u* threshold estimation across NEE, GPP and R_{eco}.

The gap-filling was performed with methods similar to Falge et al. (2001) using the marginal distribution sampling (MDS) algorithm, re-adapted from Reichstein et al. (2005) in REddyProc (Reichstein and Moffat, 2014). MDS takes into account similar meteorological data available with different window sizes (Moffat et al., 2007). Parallel to this approach, the original EC NEE data was also gap-filled with an independent AC NEE dataset (2010-2013). AC data were collected simultaneously with EC data, and so can be used to cross check. The EC NEE was predicted from AC NEE based on linear regression models. The subsequent product was gap-filled using the MDS algorithm (REddyProc).

The separation of NEE into its two main components (GPP and R_{eco}) was achieved applying two approaches: (1) the REddyProc partitioning tool (Reichstein and Moffat, 2014) and (2) a light response curve (LRC) approach (Lindroth et al., 2007; Lund et al., 2012). A brief description of each flux partitioning method is provided in the Supplementary material S1.

2.3.3 Flux uncertainties

In order to estimate the NEE gap-filling uncertainty, three different sources of uncertainty were assessed. First, we addressed the 95% confidence interval of the EC prediction based on AC data. Second, the random uncertainty of filled half-hourly values was inferred by the spread of variable with otherwise very similar environmental conditions. REddyProc uses the gap-filling to estimate an observation uncertainty also for the measured NEE, by temporarily introducing artificial gaps (T. Wutzler and M. Migliavacca (BGC-Jena), personal communication). Finally, the uncertain estimate of u* threshold was

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addressed. In the u*-NEE relationship we want to exclude the probably false low fluxes (absolute NEE values) with low u*. When choosing a lower u* threshold, also the lower flux will contribute to the gap-filling and the annual sums. Therefore, there is a tendency of a lower absolute NEE associated with lower u*. The difference between the 5% and 95% of bootstrap provides a means of the uncertainties based on the u* filters. All these sources of uncertainties were summed and propagated over time. Moreover, the GPP and R_{eco} uncertainties include the bias from the one-to-one flux comparison obtained from each model. The micrometeorological sign convection used in this study present uptake fluxes (GPP) as negative, while the released fluxes (R_{eco}) are shown as positive.

2.4 Identifying environmental forcing

Snow- and phenological-related variables such as end of the snowmelt period, start, end and length of the growing season are important components shaping the arctic CO_2 dynamics. In this study we defined the end of the snowmelt period as the day of year when less than 20% of the surface of the fen was considered snow free; the threshold was chosen in agreement with suggestions previously reported in Hinkler et al. (2002) and Westergaard-Nielsen et al. (2015). For the start, end and length of the growing season (GS_{start}, GS_{end}, GS_{length}); the GS_{start} and the GS_{end} were defined as the first and last day when the 3-days NEE average was negative (i.e. CO_2 uptake) and positive (i.e. CO_2 release) respectively (Aurela et al., 2004), while GS_{length} is the number of days between GS_{start} and GS_{end}).

A Random Forest machine-learning algorithm (Breiman, 2001; Pedregosa et al., 2011) was utilized in a data-mining exercise to identify how the environmental controls affect the variability of NEE, GPP and R_{eco}. Random forest calculates the relative importance of explanatory variables over the response variables. Here, we use photosynthetic active radiation (PAR), air temperatures (T_{air}), precipitation (Prec) and vapor pressure deficit (VPD) to explain the response of C fluxes (NEE, GPP and R_{eco}) to climate variability. Each decision tree in the forest is trained on different random subset of the same training dataset. The code is able to group explanatory variables and, in each final cluster, a multiple linear regression is built to reproduce fluxes as function of driving factors. This approach has been used to analyze NEE exchange for an Australian flux tower (Hinko-Najera et al., 2016) or extrapolate maps of biomass (Exbrayat and Williams, 2015; Baccini et al., 2012). This version of Random Forest sums the variable's importance up to 1 (i.e. the relative influence) that correspond to the fraction of decision in which a variable is involved to cluster the data. We applied Random Forest to assess the relative importance of PAR, T_{air}, Prec and VPD at different temporal scales (hourly, daily, weekly and monthly), aggregating them at the time scale indicated and lumping all the years together. (Table S1; supplementary material). Moreover, we also evaluated the diurnal, seasonal and annual pattern for each explanatory variable (data binned per hour, this is one Random Forest per hour, day and year respectively). To make sure that these results were not an artefact of the partitioning method that is based on a relationship between hourly R_{eco} and T_{air}, we performed the same analyses using day-time and night-time only hourly NEE as respective proxies for GPP and R_{eco}. Based on these results (Table S2, supplementary material) we concluded that the approach was robust for the Kobbefjord site.

3 Results

3.1 Inter-annual and seasonal variation of environmental and phenological variables

The annual mean temperatures documented from Nuuk (-0.5 °C), together with the measured in Kobbefjord (-0.4 °C), in the 2008-2015 period were generally warmer compared to the long time series between 1866 and 2007 ((Cappelen (2016); Figure S2; supplementary material), with an annual temperatures average of -1.5 °C (Figure 2). The 2008-2015 period temperatures also exposed a larger variability (Coefficients of variation (CV) = 283.3 %) compared to the 1866-2007 period (CV = 79.3 %). The 2008-2015 mean annual temperature measured in Kobbefjord fluctuated between -1.7 °C in 2011 and 3.4 °C in 2010. Moreover, the annual mean precipitations documented from Nuuk (885 mm), but also the measured across

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the eight years study in Kobbefjord (862 mm), were predominantly higher than the 1931-2007 mean (689 mm), although less variable (CV=30.8 % and 24.5 % respectively). Overall, 2008, 2009, 2010, 2012, 2013 and 2014 have shown warmer and wetter anomalies while 2011 and 2015 presented colder and drier anomalies compared to the long-term mean (Figure 2).

The end of the snowmelt period and the growing season start/length presented high inter-annual variability (CV are 9.5, 9.0 and 19.0 %, respectively). Kobbefjord became snow free in DOY 154 (June 3rd for non-lap years, SD=15). On average, the site switched from being a source of CO_2 to a sink (GS_{start}) on DOY 175 (June 24th, SD=20), and remained so (GS_{end}) until DOY 241 (July 29th, SD=8.4)(Table 1). The GS_{start} and the GS_{length} did not follow a consistent pattern among the analysed years, the growing season timing have fluctuated substantially. The high inter-annual variability of the GS_{start} correlated with variations in temperature, end of snow melt period and VPD ($p<0.05$). Highest variability was observed during 2009-2012. The 2010's GS_{length} was nearly twice as long as to 2011. Indeed, GS_{start} in 2011 differs only by 26 days with the GS_{end} in 2010.

3.2 Inter-annual and seasonal variation of CO_2 ecosystem fluxes

Overall, land-atmosphere CO_2 exchange measured between 2008 and 2015, omitting 2011, acted as a sink of CO_2, taking up -30 g C m^{-2} on average (range -17 to -41 g C m^{-2}) (Figure 5; Table 2). The cumulative NEE showed a characteristic pattern during the measuring period (Figure 5), with an initial loss of carbon in early spring right after snowmelt (also observed in Figure 3), followed by an intense C uptake as assimilation exceeded respiratory losses, triggered by increases in temperature, PAR and vegetation growth. This transition point matched the growing season start, when NEE switched from a net C source to a net C sink. Eventually, the ecosystem turned again into a net C source, defining the growing season end. Even with high inter-annual variability in terms of the end of snowmelt time and growing season start/length (Table 1), the results do not show a marked meteorological effect on the net C uptake. The ranges in annual GPP (-182 to -316 g C m^{-2}) and R_{eco} (144 to 279 g C m^{-2}) (Table 2) were >5 fold larger and more variable (CV are 3.6 and 4.1 % respectively) than for NEE (0.7 %). There was a tendency towards larger GPP and R_{eco} during wetter and warmer years (Figure S4, supplementary material).

The anomalous year, 2011, constituted a relatively strong source for CO_2 (41 g C m^{-2}) and was associated with a major pest outbreak, which reduced GPP more strongly than R_{eco}. The moth *Eurois occulta* data, collected from pitfall traps in the surrounding *Salix* and *Empetrum* dominated plots, showed a strong peak at the beginning of the 2011 growing season (Lund et al., in press) coinciding with the C loss intensification. In 2011 up to 2078 larvae were observed while other years only 14 (2008), 82 (2009), 186 (2010), 0 (2012) and 8 (2013). It is likely that the flux measurements in the lowland were a partial response to the *Eurois occulta* outbreak.

The strongest growing season CO_2 uptake occurred in 2012, leading to a -74.2 g C m^{-2} cumulative NEE, while it was only -12.3 g C m^{-2} during the weakest growing season in 2011 (Table 2). A lengthening of the growing season (2010 was the year with longest growing season) did not increase the net carbon uptake in this study. In other words, an earlier end of the snowmelt resulting in a longer growing season length did not lead to a stronger carbon sink. The gap-filled NEE time series (Figure 3) show there was predominantly CO_2 uptake between 06 h and 18 h West Greenland Summer Time (WGST). The fingerprints illustrate and emphasize how variable the GS_{start} and the GS_{length} were across the years, but also show the difference in magnitude of the growing season regarding carbon CO_2 uptake.

3.3 Data processing and quality

The NEE gap-filling and subsequent partitioning obtained from different approaches exposed inconsistencies in performance and specific uncertainties in the seasonal C budget computation. During the eight study years, there were 46.5 % of missing NEE data from the EddyFen station due to unfavourable micro-meteorological conditions, instrument failures, maintenance and calibration (Jensen and Christensen 2014) but also due to the rejection of fluxes with deficient quality or too low u*. In 2014 a major instrument failure forced the station to stop measurements in the middle of the season. In 2010 and 2012 there

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were two more interruptions in the measurements (data gaps of >20 days) although the problems could be repaired before the end of the season. Such prolonged gaps led to unreliable gap-filled NEE estimates. REddyProc marginal distribution sampling (MDS) algorithm tended to fill these large gaps with high peaks of respiration at noon times, coercing C uptake underestimation. For this reason, an independent AC NEE dataset (2010-2013) was tested to gap-fill EC data (Figure S3; supplementary material). The R^2 obtained from the EC-AC correlations were always > 0.70 (2010: R^2= 0.80, $p < 0.001$; 2011: R^2= 0.72, $p < 0.001$; 2012: R^2= 0.80, $p < 0.001$; 2013: R^2= 0.84, $p < 0.001$). The number of gaps was reduced by 18.5% and it was found that the random uncertainty from the combination of AC and MDS algorithm decreased 5% on average. By using the u*filtering and the AC data together with EC, there was an increase of ca 6 % in terms of C sink strength. Moreover, the propagated uncertainty in NEE never exceeded ±1.8 g C m^{-2}, mainly because the error related to u* filtering was low. Further, we hypothesized that different flux partitioning approaches would lead to different estimates of GPP and R_{eco}, however, the results suggest a relatively good agreement (Figure 4). There was a higher degree of agreement with regard to GPP compared with R_{eco}. LRC tended to calculate larger GPP and R_{eco} compared to REddyProc, 12 % and 15 %, respectively.

3.4 Environmental forcing

The daily aggregated NEE-GPP relationships display consistent linear correlation (2008-2015: R^2= 0.77, $p < 0.001$) across the assessed years (Figure 6a). The linear correlations were weaker in 2010 and 2011. A hysteresis was detected in 2010 (i.e. long growing season with higher R_{eco} in autumn compared to spring), while strong C releases have been observed in 2011 across June and July. The relation between GPP and R_{eco}, which can be understood as the degree of coupling between inputs and outputs, and therefore the residence time of fixed C, has shown non-linear patterns (Figure 6b). The curved behaviour is likely because GPP increased more than R_{eco}. Moreover, R_{eco} lagged behind GPP due to (1) the vegetation green-up in the first part of the growing season and (2) the higher respiration rates due to increased biomass in the second part. It is worth mentioning the high variability of C sink strength between summer months (June, July and August). The years with clearer hysteresis coincide with the years with positive temperature anomalies (i.e. 2010, 2012 and 2013) of the 2008-2015 series.

The importance of variables (such as PAR, T_{air}, VPD and Precipitation) obtained from Random Forest at different temporal scales (hourly, daily, weekly and monthly) revealed differences in behavior depending on the time aggregation utilized (Figure 7). PAR dominated NEE and GPP while T_{air} correlated the most with R_{eco} in hourly averages, whereas T_{air} became increasingly important at longer temporal aggregations for all the fluxes (Figure 7). VPD and precipitation were not found to be as important as the other variables while the use of water table depth in the analysis was discarded due to its very low impact on CO_2 fluxes. In general, NEE and GPP showed similar performances, reinforcing the linear relationships found between NEE and GPP (Fig 7). The standard deviation of the importance's variables (across 1000 decision trees) tended to increase at coarser time aggregations.

Changes of environmental forcing (PAR, T_{air} and VPD) across diurnal, seasonal and annual time scales reveal patterns of functional responses to C fluxes. The diurnal cycle analyses on hourly data showed the changes in importance between day- and night-time (Figure 8). NEE and GPP had two predominant variables (T_{air} and PAR) determining the variability at day-time. There was a significant decline of T_{air} importance early in the morning, coinciding with a peak of PAR at 06 h. WGST, triggering the C uptake. T_{air} rapidly turned back as a primary driver along the day until the range 15-17 h. WGST, when it momentarily dropped down, again, due to PAR's influence. On the other hand, R_{eco} was mainly driven by T_{air} at both night-time and day-time. VPD and PAR barely had an impact on CO_2 release. The seasonal pattern importance showed PAR dominating NEE and GPP from early June to early October (Figure 8), while T_{air} and VPD became more important before and after the snow free conditions. In terms of CO_2 release (R_{eco}) the pattern is less clear and noisier, although T_{air} appeared to be the less limiting factor. Finally, the annual pattern exposes a performance in line with previous results, i.e. PAR

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dominated NEE and GPP while R_{eco} was more sensitive to variations of T_{air}. Interestingly, the Random Forest analysis catches a decrease of PAR's importance in 2011, same year exposing the sharp decrease of C sink strength.

4 Discussion

4.1 Inter-annual and seasonal variation of CO_2 ecosystem fluxes

The balance between the two major gross fluxes in terrestrial ecosystems, photosynthetic inputs (GPP) and respiration outputs (R_{eco}), has experienced larger temporal variability than NEE (CV are 3.6, 4.1 and 0.7 % for GPP, R_{eco} and NEE, respectively). These results suggest that both GPP and R_{eco} were strongly coupled and sensitive to meteorological conditions such as insolation and temperatures (Figure 7 and 8). Interestingly, the tendency to wetter and warmer conditions led to greater rates of C cycling associated with larger GPP and R_{eco} (Figure S4, supplementary material). The mirror effect observed from the ranked cumulative GPP and R_{eco} (Figure 5) also suggest that the relative insensitivity of NEE to climate could be the result of the correlated response of both GPP and R_{eco}. Further, this study suggests that a longer growing season does not necessarily increase the net carbon uptake (Parmentier et al., 2011), since 2012 presented stronger C sink strengths (i.e. more negative NEE) than 2010. Thus, the effects on C balance of warming from climate change are not straightforward to infer.

NEE exchange measured in Kobbefjord from 2008 to 2015 indicates a consistent sink of CO_2 (within a range of -17 to -41 g C m^{-2}) with exception of the year 2011 (+41 g C m^{-2})(Table 2). The year 2011, associated with a major pest outbreak, reduced GPP more strongly than R_{eco} (Figure 5) and Kobbefjord turned into a strong growing season C source within an episodic single growing season. The return to a substantial cumulative CO_2 sink rates following the extreme year of 2011 shows the ability of the ecosystem to recover from the disturbance. Indeed, the ecosystem not only shifted back from being a C source to a C sink, but it also changed rapidly from one year to the next. Thus we found evidences in Kobbefjord of ecosystem resilience to the meteorological variability, similar to other cases described in other northern sites (Peichl et al., 2014; Zona et al., 2014). Only a few references sites have reported similar decreases in net C uptake, but in no case as large as the one observed here. Zona et al. (2014) described an effect of delayed responses to an unusual warm summer in Alaska. Their results suggested that vascular plants, which have enhanced their physiological activity during the warmer summer, might have difficulties readapting to cooler, but not atypical, conditions, which have provoked a significant decrease of GPP and R_{eco} the following year. In their study, the ecosystem returned to be a fairly strong C sink after two years, suggesting strong ecosystem resilience. Moreover, Hanis et al. 2015 have reported comparable C sink - C source variations in a Canadian fen within the growing season due to changes in the water table depth. Drier and warmer than normal conditions have triggered an increase in C source strength. Finally, during an extensive outbreak in a subarctic birch forest in Sweden, Heliasz et al. (2011) observed a similar decrease in net sink of C (most likely due to weaker GPP) across the growing season. However, the C source strength (NEE = 40.7 g C m^{-2}) found in 2011 at Kobbefjord was higher compared to these other cases. To our knowledge, it has not been reported such abrupt disturbance concerning C sink strength in Arctic tundra.

A combination of different factors could have led to the sharp change in C balance observed between 2010-2011, both physical and biological. The year 2010 had the highest mean annual temperature while 2011 had the lowest, 3.4 °C and -1.7 °C respectively (compared to -0.4 °C, the 2008-2015 mean annual temperature). The warmest winter-time temperature (Dec-Jan-Feb) occurred in 2010, with -2.7 °C (compared to -6.79 °C, the 2008-2015 mean wintertime temperature). These climatic conditions stimulated the thinnest (0.05 m compared to averaged 0.26 m) and short-lasting snow pack in 2010; whereas 2011 had the thickest (0.41 m compared to averaged 0.26 m) and long-lasting snow pack due to the cold summer. Consequently, 2010 experienced the longest growing season (85 days) while 2011 had the shortest (only 47 days) as well as the latest start of the growing season. Further, PAR appeared to be a limiting factor for NEE in 2011 (Figure 8). All these characteristics together may have triggered an enhanced productivity (i.e. more negative GPP) in 2010 compared to the

lowest productivity and C sink strength estimated in 2011 (i.e. least negative GPP and NEE). Finally, the noctuid moth *Eurois occulta* outbreak occurred in 2011 overlapped the abrupt decrease of C sink strength observed. Although we cannot provide a quantification of change attributed to meteorological variations and biological disturbances, there are evidences showing that the month outbreak could partially has decreased the C sink strength in Kobbefjord. In an undisturbed scenario, the meteorological conditions in 2015, colder and dryer than the mean 2008-2015 period (Figure 2), but similar to 2011, would have stimulated similar behaviours in terms of C fluxes. However, the cumulative fluxes in 2015 (Figure 5) followed analogous patterns compared to the rest of the years. This evidence agrees with literature (Callaghan et al., 2012b; Lund et al., in press) on the fact that tundra systems can fluctuate in sink strength influenced by factors such as episodic disturbances or species shifts, events very difficult to predict.

4.2 Data processing and quality

The NEE gap-filling and subsequent partitioning exposed inconsistencies in performance and specific uncertainties in the seasonal C budget computation. The uncertainties found underlays the strong challenges related to accurate gap-filling and partitioning estimations. In this study, we used a marginal distribution sampling (MDS) gap-filling technique, an enhancement to the standard look up table (LUT). Both methods have shown a good overall performance compared to other procedures such as non-linear techniques (NLRs) or semi-parametric models (SPM), but slightly inferior to artificial neural network (ANN) (Moffat et al., 2007). However, the algorithm has shown a flaw in performance across the two extensive and uninterrupted gaps in 2010 and 2012 (Figure S3, supplementary material). Estimated NEE during these periods were unrealistic and led to marked NEE underestimations (i.e. lower CO_2 sink strength).

The NEE partitioning obtained from REddyProc and LRC suggests a relatively good agreement in model performance. The one-to-one comparison between different approaches found a better agreement with regard to GPP compared to R_{eco}. LRC GPP was 12 % higher than REddyProc GPP; while LRC R_{eco} was 15 % higher than REddyProc R_{eco}. In this analysis, REddyProc produced smoother R_{eco} estimates compared to the noisier GPP estimates, whereas LRC performed the other way around. This is mainly because measurement noise goes into GPP for REddyProc method, and into R_{eco} for LRC method. REddyProc retrieves positive GPP values whereas LRC method results in negative R_{eco} values. Both scenarios are not fully convincing, although it is not straightforward how they should be treated. By removing all positive GPP / negative R_{eco} values would risk removing only one side of the extremes. Besides night-time based (REddyProc) and day-time based (LRC) partitioning approaches, several implementations have been proposed to improve the algorithms performance. Lasslop et al. (2010) has modified the hyperbolic LRC to account for the temperature sensitivity of respiration and the VPD limitation of photosynthesis. Further, Runkle et al. (2013) proposed a time-sensitive multi-bulk flux-partitioning model, where the NEE time series was analyzed in one-week increments as the combination of a temperature-dependent R_{eco} flux and a PAR-dependent flux (GPP). However, it remains uncertain under which circumstances each partitioning approach is more appropriate, especially in the boundaries between low- and high-Arctic due to the lack of dark night along polar days (where the light is / is not respectively a limiting factor for the plant growth). Since there are few methods with an unclear precision, an evaluation study on the effect of using different partitioning approaches along latitudinal gradients would be very beneficial to assess the suitability for each method.

4.3 Environmental forcing

The analyses at different temporal scales demonstrate distinct C flux responses to different environmental forcing. The hourly variability of NEE and GPP has been found to be mostly dependent on PAR, while R_{eco} was linked to T_{air} primarily. In order to circumvent the potential circularity conflicts based on the use of partitioning products, we filtered day-time NEE (true GPP) and night-time NEE (true R_{eco}), obtaining very similar results (Table S2, supplementary material). On the other hand, the daily, weekly, and monthly C flux variability were mainly driven by T_{air}. These results entirely agree with Lindroth

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et al (2007), who recognized T_{air} as a main driver for NEE seasonal trends in northern peatlands. Overall, the results indicate that environmental factors that can change rapidly (e.g. PAR) will have a high influence on short time scales. Regarding temperatures, the photosynthesis is restricted by low temperatures, so enzymatically driven processes such as carbon fixation are more sensitive to low temperatures than the light-driven biophysical reactions (Chapin et al., 2011).

The changes of environmental forcing across diurnal, seasonal and annual time scales unmask patterns of functional responses to C fluxes. Interestingly the Random Forest analyses revealed a strong diurnal pattern with a marked contribution of T_{air} to variations in NEE and GPP (both at night-time and between 08-18 h WGST) while T_{air} was more important involving R_{eco}. It is also interesting to see how PAR increased importance at 08 h and 20 h WGST, coinciding with the sharp gradient in light at dawn and dusk. The seasonal pattern showed PAR as the single main driver for NEE and GPP between early June and early October, supported by the longer day-time and the decrease in cloudiness.

In this study, environmental drivers related to water availability such as VPD and precipitations were not found to be as influential as other assessed variables. We have not found significant relationships between CO_2 fluxes and the water table depth either. Thus, there was not apparent water limitation on carbon dynamics during the eight years period. However, the complex interactions based on changes in temperature and soil moisture regarding C dynamics seems to be still not fully understood, and these should be further explored in the Arctic tundra context. Our results contrast with Strachan et al. (2015) who described water table depth as an important driver regulating the CO_2 balance and others who found that CO_2 emissions increase during dry years due to increased decomposition rates and a reduction in GPP (Aurela et al., 2007; Lund et al., 2007; Oechel et al., 1993; Peichl et al., 2014); whereas other sites act as sinks during relatively wet years (Lafleur et al., 1997).

5 Conclusions

An improvement in our understanding of the C balance in the Arctic, and its climate sensitivity, is important for understanding the response of tundra ecosystems to a changing climate. We have analyzed eight snow-free periods in eight consecutive years in a West Greenland tundra (64° N) focusing on the net ecosystem exchange (NEE) of CO_2 and its photosynthetic inputs (GPP) and respiration outputs (R_{eco}). Kobbefjord acted as a consistent sink of CO_2, accumulating -30 g C m^{-2} on average (range -17 to -41 g C m^{-2}) during the years 2008-2015, except 2011 that was associated with a major pest outbreak. The results do not show a marked meteorological effect on the net C uptake. The relative insensitivity of NEE was a compensation between the response of GPP and R_{eco}. The ranges in annual GPP (-182 to -316 g C m^{-2}) and R_{eco} (144 to 279 g C m^{-2}) were >5 fold larger and more variable (CV are 3.6 and 4.1 % respectively) than for NEE (0.7%). GPP and R_{eco} were sensitive to the insolation and the temperatures and, interestingly, it was found a tendency towards larger GPP and R_{eco} during wetter and warmer years. The anomalous year, 2011, constituted a relatively strong source for CO_2 (41 g C m^{-2}) and could partially has decreased its C sink strength due to the biological disturbance, which reduced GPP more strongly than R_{eco}. The importance of variables at different temporal scales revealed differences in behavior depending on the time aggregation utilized. PAR dominated NEE and GPP while T_{air} correlated the most with R_{eco} in hourly averages, whereas T_{air} became increasingly important at coarser temporal aggregations for all the fluxes. The changes of environmental forcing across diurnal, seasonal and annual time scales unmasked patterns of functional responses to C fluxes.

Despite the fact that we have analysed an eight-year dataset, the results should be taken cautiously due to the incomplete picture based on the lack of round year data (Grøndahl et al., 2008). Even when wintertime is not as critical as summertime period, this part of the year should be taken into account for a comprehensive understanding of complete C budgets and the delayed effect of wintertime-based variables such as snow depth or snow cover on the C fluxes. Since some studies have suggested that GPP and R_{eco} have increased with observed changes in climate and NEE trends remain unclear (Lund et al., 2012), it is challenging to come up with strong evidences while the data remains scarce and fragmented. Hence, there is a

need for increased efforts in monitoring of Arctic ecosystem changes over the full annual cycle (Grøndahl et al., 2008; Euskirchen et al., 2012). Future work will include C flux modelling in order to dig into process-based insights of C exchange balance in the Arctic tundra.

Author contribution

E. López-Blanco, M. Lund, M. Williams, T.R. Christensen and M.T. Tamstorf designed the experiment. Data preparation and analysis was primarily performed by E. López-Blanco with contribution from M. Lund (eddy covariance data processing, data quality control and LRC partitioning), M. Williams and T.R. Christensen (experimental set up), B.U. Hansen (data gathering from Nuuk Ecological Research Operations, GeoBasis), A.Westergaard-Nielsen (daily estimate of the timing of snowmelt) and J.-F. Exbrayat (Random Forest approach). E. López-Blanco prepared the manuscript with active contributions from all co-authors.

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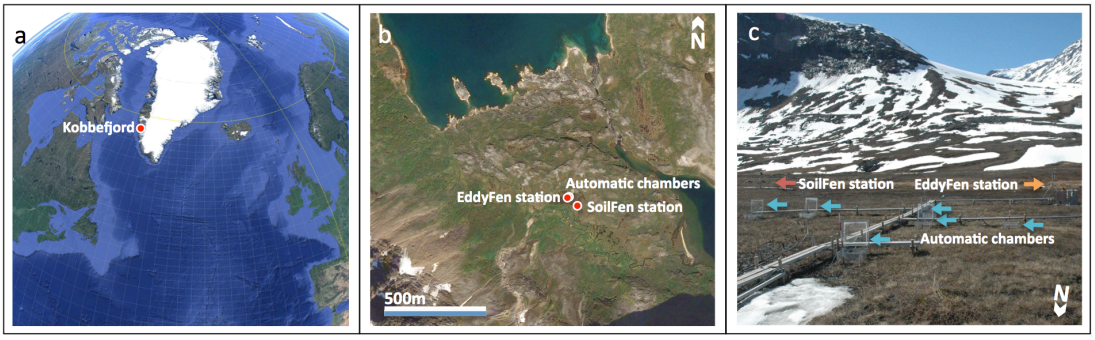

Figure 1: (a) Location of Kobbefjord in Greenland, 64° 07' N; 51° 21' W (Source: Google Earth Pro). (b) Location of EddyFen station, automatic chambers and SoilFen station in Kobbefjord (Source: Google Earth Pro, 16-07-2013). (c) Eddy covariance (orange arrow) from EddyFen station, six automatic chambers (light blue arrows) and SoilFen station (pale red arrow)(photo by Efrén López Blanco, 27-06-2015).

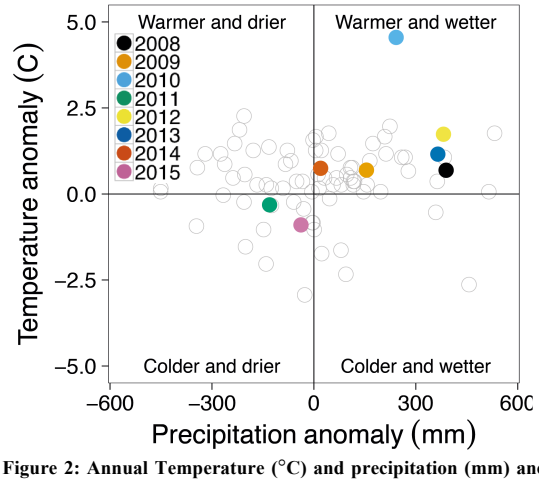

Figure 2: Annual Temperature (°C) and precipitation (mm) anomalies of the analyzed years (2008-2015) compared to the 1866-2007 time series shown as empty circles (Cappelen, 2016).

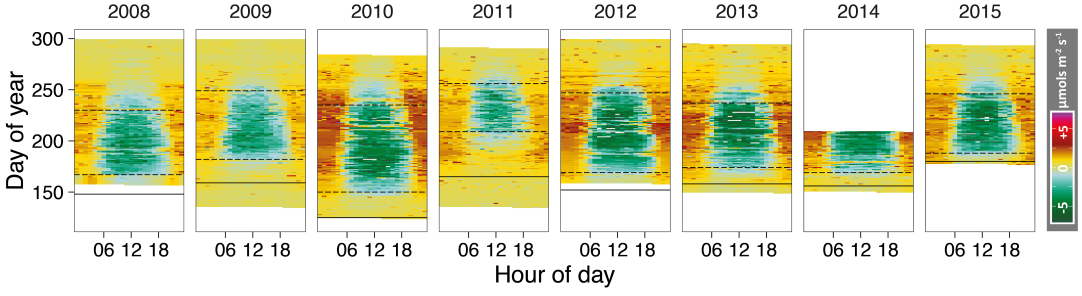

Figure 3. Time series of gap-filled NEE (2008-2015) based on auto-chamber data (2010-2013) and the MDS algorithm (from REddyProc). Green represents C uptake while the orange-dark red denotes C release. The solid lines represent the end of the snow melt period while the area within the dashed lines represent the period between the start and the end of the growing season.

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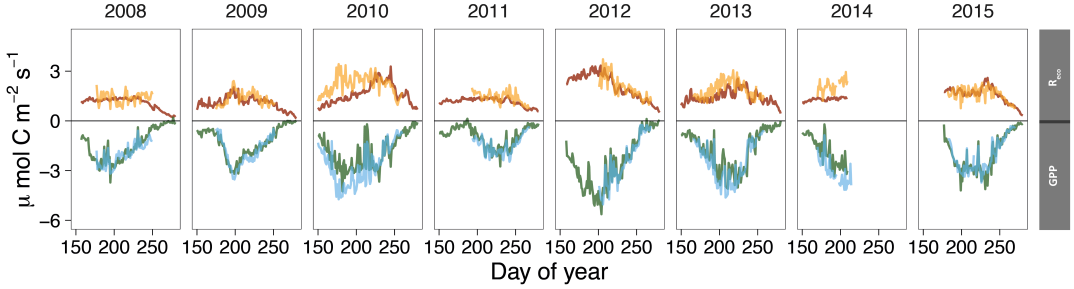

Figure 4. Time series of daily mean GPP (negative fluxes) and R_{eco} (positive fluxes) from 2008 to 2015 calculated by REddyProc (dark green and dark red) and LRC (orange and light blue).

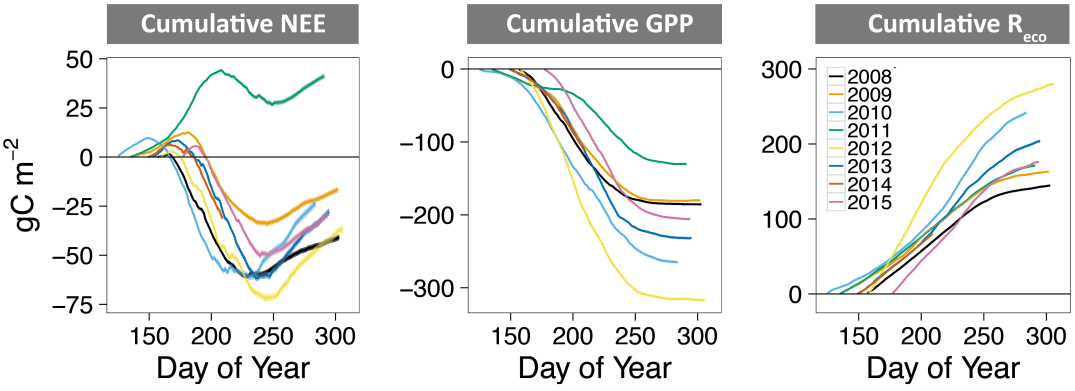

Figure 5. Cumulative NEE, GPP, and R_{eco} from 2008 through 2015 including the u* filtering and random errors.

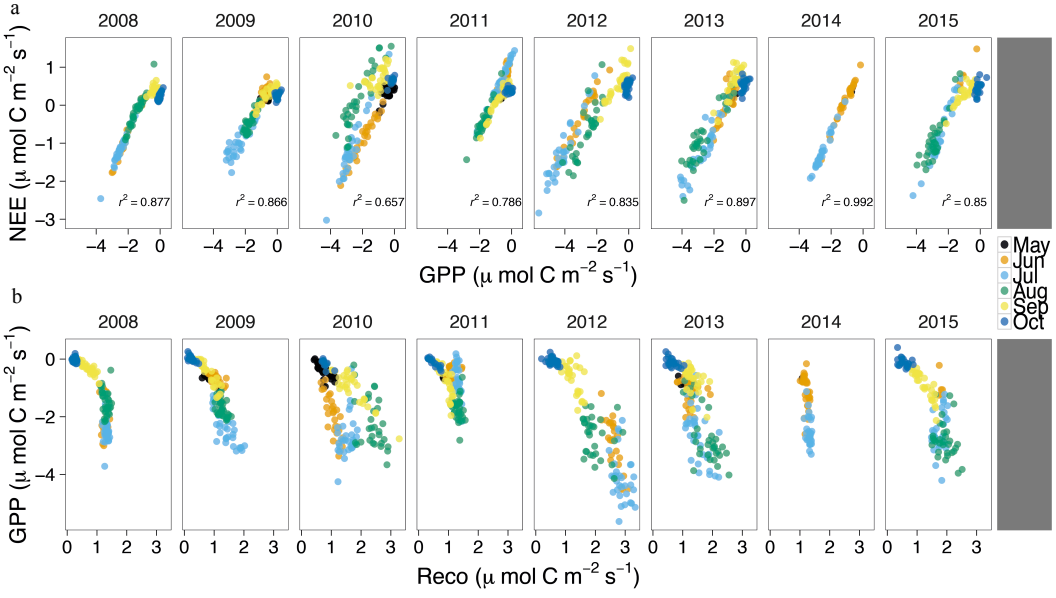

Figure 6. Inter-annual variability between (a) NEE-GPP and (b) GPP-R_{eco} relationships. The data was daily aggregated and colored per month

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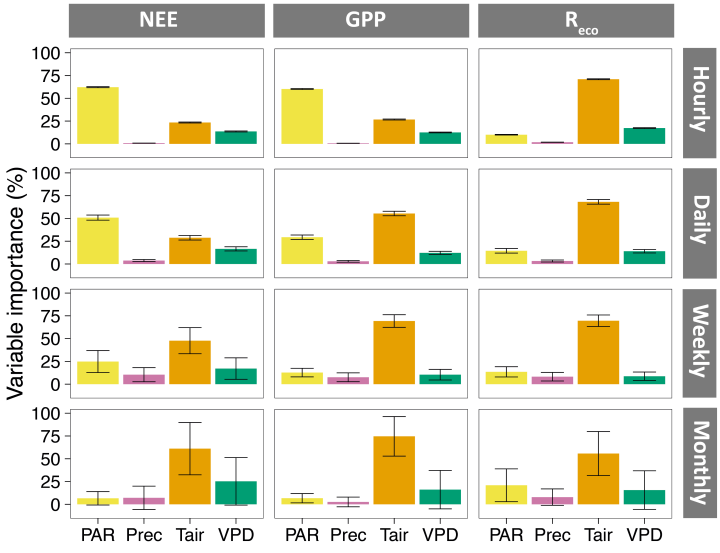

Figure 7. Importance of environmental variables PAR (yellow), T_{air} (Orange), Prec (pink) and VPD (green) to explain variability in NEE, GPP and R_{eco} (partitioned by REddyproc) at different temporal aggregations (hourly, daily, weekly and monthly) when all the years were lumped together. Thick bars and error bars represent the mean ± standard deviation of the importance across 1000 decision trees.

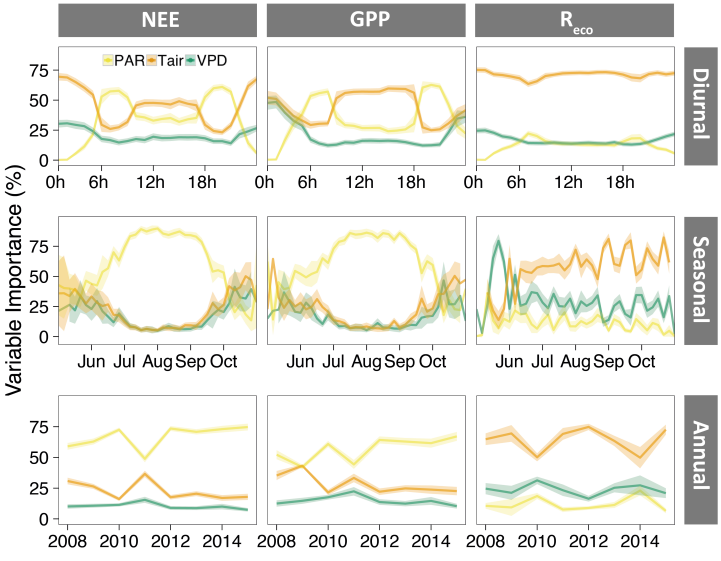

Figure 8. Diurnal, seasonal and annual importance of environmental variables PAR (yellow), T_{air} (Orange), and VPD (green) to explain variability in NEE, GPP and R_{eco}. Thick lines and shading represent the mean ± standard deviation of the importance across 1000 decision trees.

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675 **Table 1. Summary of the phenological-related variables for the period 2008-2015.**

	2008	2009	2010	2011	2012	2013	2014	2015
Maximum snow depth (m)	0.6	1.0	0.3	1.4	1.0	0.6	1.1	1.2
End of snowmelt period (DOY)	148	159	125	165	152	158	156	176
Beginning of growing season (DOY)	167	182	150	209	169	174	169	188
End of growing season (DOY)	230	249	235	256	247	237	-	246
Length of growing season (DOY)	63	67	85	47	78	63	-	58

Table 2. Summary of the measuring periods and the growing season CO2 fluxes for the period 2008-2015.

	2008	2009	2010	2011	2012	2013	2014	2015
First measurement (DOY)	157	135	124	135	158	149	150	177
Last measurement (DOY)	303	304	282	287	305	295	209*	294
Missing data (%)	57.6	42.3	28.6	35.4	32.3	29.8	44.9*	40.0
NEE in measuring period (g C m^{-2})	-41.3	-16.9	-24.4	40.7	-37.0	-28.1	-28.7*	-31.5
	±1.4	±1.4	±1.9	±1.3	±1.8	±1.7	±1.1	±1.6
NEE in growing season (g C m^{-2})	-62.3	-45.9	-70.0	-16.2	-74.2	-69.7	-35.3*	-55.8
Maximum daily uptake (DOY)	195	205	182	230	204	220	192*	199
Maximum uptake (µmols m^{-2} s^{-1})	-2.4	-1.7	-3.0	-1.4	-2.8	-2.5	-1.9*	-2.3
Estimated GPP (g C m^{-2})	-185.5	-181.8	-266.1	-130.6	-316.2	-230.7	-106.8*	-206.1
	±1.4	±1.4	±1.9	±1.3	±1.9	±1.7	±1.1	±1.6
Estimated R_{eco} (g C m^{-2})	144.2	164.9	241.6	171.3	279.2	202.6	78.1*	174.6
	±1.3	±1.3	±1.8	±1.2	±1.8	±1.7	±1.1	±1.5

where applicable: ± sum of the auto-chamber, random and u* filtering uncertainties, * incomplete growing season dataset.

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